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Abstract

At the close of the National Wind Tunnel Complex project (NWTC), just prior to entering the detailed design phase, a baseline test section with porous-slotted walls had been defined. The purpose of this paper is to present the development of the concept features of the wall configuration presented at the Systems Design Review (SDR) at the close of the project in the context of the evolution of the NWTC project. Slot width and spacing, along with slot-baffle inserts to provide desirable control of test section crossflow and acoustic characteristics, were defined. Flow quality requirements concerning stream angle homogeneity at the outer edge of the test volume, requirements for maximum wall interference, optical access, and test volume acoustic considerations in addition to Mach number range and tunnel operational mode were factors in the design. The development process included 2D calculations for stream angle homogeneity to establish slot width and spacing, 3D calculations which initiated the acceptance of segmented control of slot crossflow, supporting 3D calculations for verification of slot geometry and crossflow control, and experimental development of slotbaffle insert geometry that would be rugged, allow control of crossflow, and not produce strong resonant tones. Results of 2D calculations, 3D calculations to illustrate need for control of crossflow, and experimental evaluation of baseline slotbaffle acoustic properties are presented.

Introduction:

The National Wind Tunnel Complex (NWTC) Program initially was envisioned as providing US Industry, the Department of Defense (DoD) and NASA with two new large wind tunnels that would satisfy the low-speed and transonic wind tunnel production testing needs of the Nation for the next 40 to 50 years. An NWTC project status report published as AIAA 96-0226[1] and the NWTC Final Report[2] provides details of the National Wind Tunnel Complex Project history, including background information that traces the origins of the project. The central theme was to "acquire a '*best in the world, not to be surpassed*' development facility to support the U.S. airplane industry."[3] To accomplish this goal, it was assumed that a leap ahead in wind tunnel design from conventional technology would be required on all aspects pertaining to the NWTC. The design of the test section was just one area. The purpose of this paper is to highlight the thinking and study that went into the development of the porous-slotted wall geometry that evolved from the NWTC project activities.

NWTC test section evolution:

At the inception of the project, two high-performance wind tunnels were already envisioned. These were a low-speed tunnel, including an open-jet capability, and a transonic wind tunnel with a Mach number range spanning low speed to Mach number 1.5. In the original concept, the low-speed wind tunnel was to have a 20- by 24-ft test section and the transonic tunnel was to be 11 by 15.5 ft. The test section walls for these tunnels were to be porous-slotted[4] with variable crossflow control capability and acoustic treatment in the slots to suppress slot tones. The slotted wall arrangement was deemed necessary to provide sufficient optical viewing capability. Further, it was a given condition that the NWTC have continuous operational capability up to Mach number 1.5 with reasonably good supersonic flow quality. Therefore, porous slots, as opposed to conventional open slots (e.g., National

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Transonic Facility) were considered necessary to improve the supersonic flow forming and wave cancellation properties.[5] This view was supported by NACA work in the development of the Ames Unitary Plan Wind Tunnel's 11- by 11-ft transonic test section (11-ft tunnel) which was reported by H. J. Allen.[6] Allen showed that with sufficient lines of porosity (porous slots), the wall will behave as if it is uniformly porous. Figure 1, taken from Ref. 6, shows that for a wall with porosity held constant, there is virtually no change in reflected disturbance after the wall porosity is formed by eight or more lines of perforation. It also shows that it takes about three times as many open slots to achieve the same trend of constant reflected disturbance. However, the magnitude of the reflected disturbance for open slots is greater than for lines of porosity (porous slots).

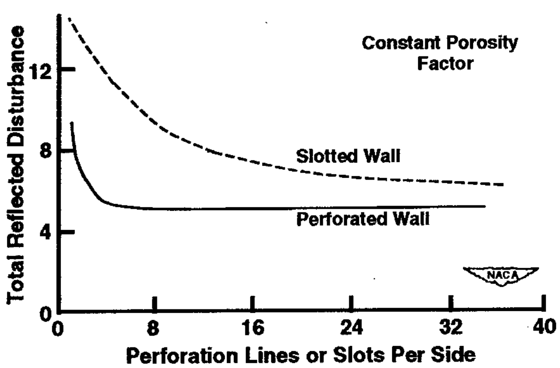


Figure 1. Effect of lateral spacing of slots and performations.

The porous slot concept for the NWTC was expected to be formed by inserting baffles similar to the Ames 11-ft Transonic Wind Tunnel[5] in the constant-width slots. Figure 2 shows the arrangement for the slot-baffles in the 11-ft tunnel. Here, the baffles divide the constant-width slot into a series of triangular cross-section shaped channels that are perpendicular to the stream surface, thus creating the equivalent of a line of porosity. Referring to Figure 2, a conventional open slot differs from the 11-Foot design in that there is no baffle present and the slot is usually of varying width at the upstream and downstream end of the test section to provide transition of flow into and out of the plenum chamber in those regions. This type of open slot is typical of most test sections with slot-

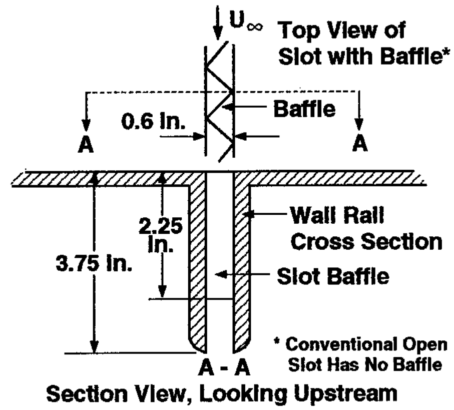


Figure 2. Ames 11-ft W.T. slot-baffles.

ted walls such as the National Transonic Wind Tunnel (NTF). The baseline NWTC slot-baffle design is similar to the design of the 11-Foot Tunnel shown in Figure 2 in that the baffles form triangular cross-sectioned channels, but it is different in that the axis of each channel is inclined toward the free-stream flow by 30 degs from the perpendicular and the depth of the baffle extends the full depth of the slot. This 30-deg inclination angle was based on work performed by AEDC[7,8] under the sponsorship of NASA Ames and further unpublished work by the author as a NASA employee.

A baseline slot width of 1.5 in. with a slot-center to slot-center spacing of 15 in. for the transonic test section was identified on the basis of flow quality at the outer edge of the required test volume. The slot width and spacing reported herein was based on 2D analysis and was confirmed by Bussoletti et el[9] in an inviscid numerical study of a 767-300 wing/body configuration in the NWTC test section.

It was assumed that something other than a fixed crossflow characteristic wall would be required for reduction of wall interference for both the low-speed and transonic wind tunnels, as well as the establishment of best supersonic flow quality for the transonic test section. The use of a fully adaptive wall in each of the test sections was not viewed as being affordable, as well as practical, in view of the requirement for productivity substantially greater than current production wind tunnels. Consequently, it was foreseen that a variable crossflow control concept would be required. The expected solution for crossflow control was to use

baffles extending the full depth of the slot in conjunction with a segmented sliding cut-off plate on the plenum side of each slot to provide variable crossflow resistance. Slot tone noise suppression was expected to be accomplished by the addition of features such as splitter plates on the stream surface of the slot or a grid or screen overlay to help suppress shear-layer interactions that would create discrete tones. An initial test in the Ames 14-ft tunnel[10] was conducted to evaluate the acoustic disturbance generating properties of candidate slot-baffle configurations. Other tests to improve the slot-baffle design and to validate test section flow development and expected crossflow resistance were also to have been accomplished early in the detailed design phase of the project. Further, in view of the expected difficulty in achieving very low test section noise levels, continuous improvements to the slot-baffle design for acoustic properties were envisioned but not planned at the close of the project.

Before the Ames 14-ft test could be executed, changes in the concept for the NWTC occurred because the projected cost figures for the two-tunnel approach ($2.5B) proved untenable. In late 1995, the decision was reached to de-scope the project to attempt a design to a $1.2B funding limit. The goal was to achieve as many of the original NWTC requirements as possible. A single, multipurpose wind tunnel (MPWT) with a 13- by 16-ft test section evolved from this effort. The baseline 1.5-in. slot width and 15-in. slot spacing for the transonic tunnel was retained since the major dimension of the former test section was only less by 6 in. from the 16-ft width of the MPWT. The length of the control segments was increased from the original 30-in. length to 48 in. to reduce costs. This increase in length of control segment was justified by inviscid 3D calculations performed by Sickles & Steinle.[11] The recommended open area ratio was 10 percent. ASE FluiDyne presented options within these guidelines and recommended 44 slots (12 on each of the top and bottom walls and 10 on the side walls).[12] As seen in Fig. 3, this arrangement of the slot spacing resulted in a 12.75-in. distance between the side walls and the floor or ceiling slot nearest the respective wall for the 0-deg wall setting (parallel side walls). Correspondingly, the distance between the slot on the

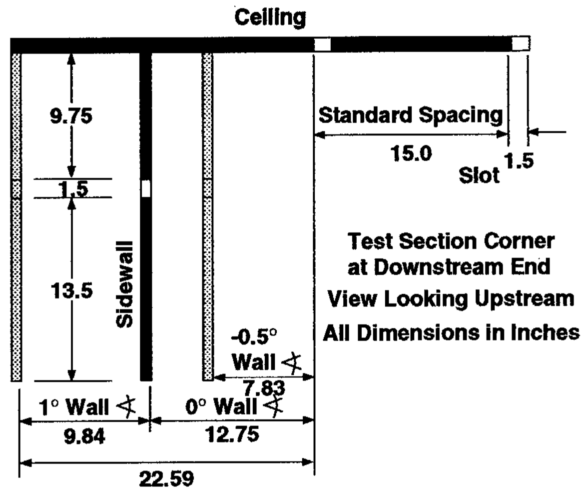


Figure 3. Slot spacing and range of sidewall motion.

side walls and floor or ceiling is 9.75 in. With the side walls fully converged (-0.5 deg), the distance between each side wall at the end of the 47-ft working section is reduced by 4.92 in. which results in a clearance of 7.83 in. In the fully diverged position (1.0 deg), the clearance between the adjacent floor or ceiling slot and the corresponding side wall increases to 22.59 in. This large distance gives rise to concern for boundary-layer growth-related problems. Conceivably, it may be better to have an additional slot on the side wall in each of the corners to help prevent boundary-layer growth leading to secondary flow problems. A slot of fixed geometry without variable crossflow capability is seen as a distinct possibility. The necessity for these additional corner slots has not been investigated.

A major test section design challenge was the accommodation of the extensive amount of optical window and instrumentation capability, the slot flow mechanism, and the box beam structure necessary to carry the pressure loading on the wall without excessive deflection. The concept design of the test section wall structure, integrating all of these features, was performed by ASE-FluiDyne.[13] Figure 4 shows a cross section of the test section box beam structure which includes the optical windows and cut-off plate mechanism concept. In Fig. 4, the amount of optical access (window area and volume for instrumentation) is seen to be substan-

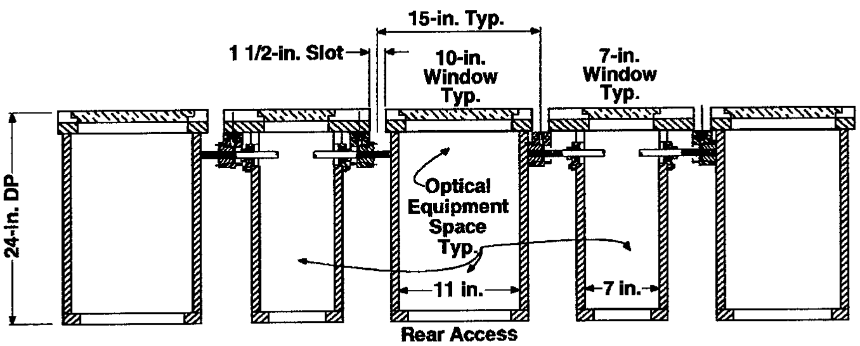


Figure 4. Test section box beam, slot flow throttle and optical access concept.

tial; however, the amount of access is a compromise over what was desired for optimum viewing.

In March 1996, the decision was reached to call a halt to the NWTC program. At this point, the most favorable assumed cost was $1.29B with assumed site-provided equipment valued at $0.37B. When the decision to halt the project was reached, it was decided to continue with the test in the Ames 14-ft Wind Tunnel. The project was essentially terminated with the Systems Design Review (SDR) for the MPWT[14] which was held March 20-22 while the 14-ft test program was in progress. The final report for the project and final close-out details, including archiving all project material on CD-ROM, did not occur until June 1996.

The details of the 14-ft test program and results obtained are contained in the project archives[10]. The baseline slot-baffle configuration (designated M12-7) which resulted from the 14-ft test program is shown in Fig. 5. The baffle configuration is made up of an alternating bent stainless steel strip (0.06 in. thick) whose bend axis is inclined upstream 30 degs from the normal to the floor to produce the triangular channels previously noted. The depth of the baffle is 2.25 in. Three, 0.75-in. deep, 0.12-in. thick, evenly spaced splitter plates divide the stream surface into a series of cells of decreasing width. This configuration was created from an earlier, less successful configuration by hand grinding the notches shown which lie approximately midway between the intersection of the baffle and the splitter plate with the next intersection (or edge of the baffle). The notches are nominally 0.08 inches wide by 0.15 in. deep. The notches were added to de-tune the shear layer interaction with the slot. The thickness of the material was chosen to produce a configuration that would be extremely robust. No analysis was done to establish the necessity for this apparently rugged design.

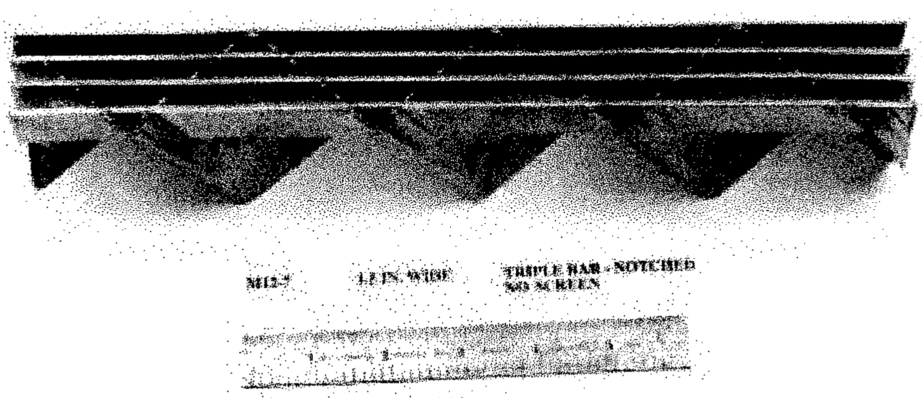


Figure 5. Baseline slot-baffle configuration.

Design Considerations Affecting Slot Width and Spacing:

Flow Quality - Flow Angle

An estimate of the spatial variation in flow angle induced by the nonuniformity caused by slotted walls was determined by a 2D modeling of the flow field in a plane normal to the wall. An incompressible potential flow analysis was performed by treating the wall as periodic with uniform flow approaching the wall in the far-field. The infinite series representing the wall was approximated by truncating

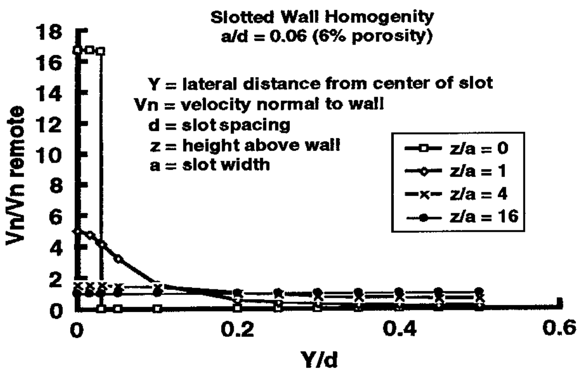


Figure 6. Normal velocity distribution for Periodic 2D slotted wall in crossflow.

with sufficient terms to capture the near-wall variation to a reasonable degree of accuracy. Calculations were performed using a wall porosity of 6 percent which is close to the optimum for a fixed, slotted wall geometry that produces a low level of wall interference. Figure 6 shows the ratio of local velocity normal to the wall to that of the remote velocity normal to the wall. This figure shows how rapidly the flow approaches a homogenous value. Very close to the wall, continuity results in the velocity at the slot approaching 1/porosity and at the slat (solid portion) it should be zero. As distance away from the wall increases (z), the flow becomes increasingly homogenous. At approximately one slot spacing away from the wall (z/a = d/a = 16), the local effects of the slot flow visually appear to be insignificant. Figure 7 shows the actual maximum variation with distance from the wall. At one slot spacing, the peak-to-peak variation is of the order of 3.8 percent. To achieve a 1%

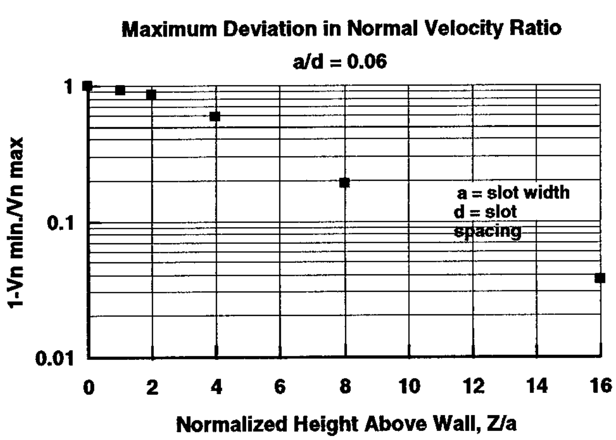


Figure 7. Maximum normal velocity distribution for periodic 2D slotted wall in crossflow.

variation (2 percent peak-to-peak) appears to require a distance between 18 and 20 slot widths. To be more definitive would require additional terms in the truncated series. A distance of 20 slot widths is equivalent to 1.2 times the slot spacing.

The magnitude of the remote normal velocity approaching the wall can be estimated from the assumption of the linear crossflow versus pressure coefficient (Cp) character of the walls. Assuming that the effective homogenous porous wall resistivity (R) for linear wall behavior matches that of a 6 percent porosity slotted wall with R = 19 (determined experimentally by the author while a NASA employee at Ames to be a reasonable representation of the Ames 11-ft TWT slotted wall):

Vn remote/ U reference = R*% porosity/200*Cp = Flow Angle (measured in radians),

where Cp is wall pressure coefficient.

Further, since the variation in flow angle divided by remote flow angle = (Vn local - Vn remote)/Vn remote;

variation in flow angle = R*% porosity/ 200*Cp*(1-Vn local/Vn remote)

Specifying an allowable variation in flow angle of 0.01 deg then leads to values of (1 - Vn local / Vn remote) as a function of Cp and R. The result for R = 19 for a wall that is 6 percent porous (a/d = 0.06) is shown in Fig. 8. For a different porosity, a new curve can be constructed by multiplying the values for a/d = 0.06 by R times % porosity/6. The allowable variation for a 10 percent porous wall is also shown. It is seen that for 0.01 deg allowable variation, and for Cp values of around 0.04 which will be representative of a large lifting model at transonic speeds, a limiting value of .01 or smaller in normal velocity variation is required.

Perturbation velocity parallel to the wall and orthogonal to the free-stream direction is examined in the same manner as for velocity normal to the wall. Figure 9 shows the range of expected variation for flow parallel to the wall. Since the wall nearest the wingtip will be the closest one to the model, the velocity parallel to the wall will be

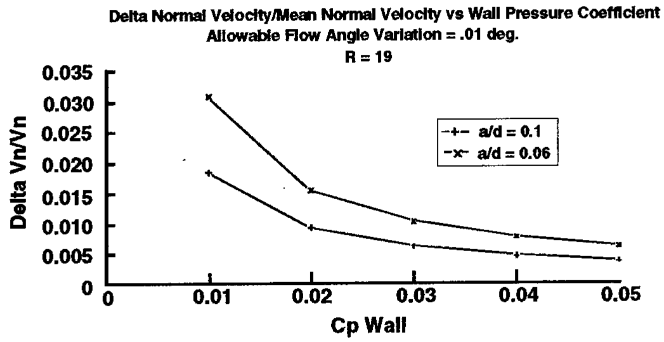


Figure 8. Allowable normal velocity increment for R = 19 porous slot.

the one of dominant interest since it affects angle of attack for the wing. The variation in normal velocity for that wall primarily alters the effective local sweep angle. For a uniform homogeneous wall, the velocity parallel to the wall due to constant mass flux through the wall would be zero because there would be no localized slot flow effects. Therefore, Vy max/U reference is the measure of the maximum variation in induced angle from the ideal since the minimum is zero. Hence, the allowable Vy max/Vn for 0.01 degrees is the same as the allowable value of 1-Vn local / Vn remote for maximum flow angle variation normal to the wall which was employed in Fig. 8. The 0.01 deg criterion employed in Fig. 8 for a 6-percent wall with Cp wall = 0.04 is seen in Fig. 9 to be reasonably satisfied for flow parallel to the wall by a distance from the wall of 1.1 slot spacing.

Having established an estimate for the allowable maximum slot spacing as being approximately equal to (distance from the wall to the wing)/1.1, full models should have at least this clearance (a minimum of 10 percent of the tunnel width for the allowable largest model spanning 80 percent of the distance between walls). For a full-span model in a test section of 16 ft width, this leads to 0.1*16*12/1.1 = 17.4 in. An 80 percent half model mounted off the floor with 13-ft test section height would allow .1*2*13*12/1.1 = 28.4 in. An additional factor affecting the choice of slot spacing is the need to have an even number of slots in the floor and ceiling to accommodate instrumentation and model alignment systems on the test section wall centerline. Although it is not as critical, it is better to have an even number of slots in the side wall as well, since the primary problem is accommodation of the interference from the trailing vortex as opposed to the bound vortex. This argues for the same number of slots above the sidewall centerline as below. From a supersonic flow development viewpoint, even slot spacing on all walls is to be preferred for the sake of uniformity.

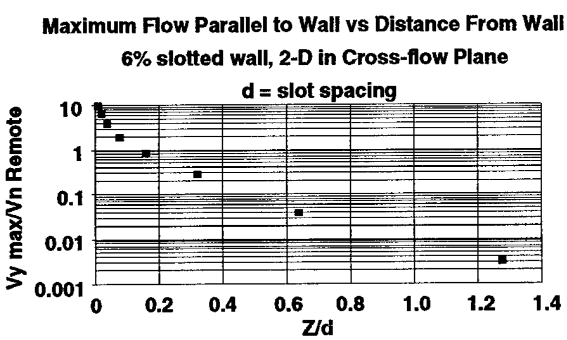


Figure 9. Maximum induced flow parallel to a 2D periodic slotted wall is crossflow.

With these points in mind, a basic slot spacing of 15 in. for the transonic test section was recommended.[15]

Flow Quality - Wall Interference

The recommended porosity for the slots was 10 percent open area to allow for flow through the walls caused by operation of the Plenum Evacuation System (PES) and to permit a range of control of the crossflow resistivity, R, both laterally and longitudinally to reduce the wall interference to an acceptable minimum. Further, since jet noise increases nonlinearly with velocity, it is preferable to have as high a porosity as practical to hold jet noise induced by PES flow to a minimum.

A basic slot width of 1.5 in. resulted in a porosity of 9.5 percent with the 44 slots proposed for the transonic tunnel. By way of comparison, the Ames 11-ft TWT has 52 slots that are approximately 0.6 in. wide, producing a wall approximately 6 percent porous. Control of flow through the slots of the NWTC test section was envisioned as being piecewise continuous for each segment. The length of the segments for control of slot flow required study.

A potential flow analysis of a wing-body representation using point singularities was done to

examine the free air normal velocity at the wall in comparison with that forced by a linear porous boundary condition. Figure 10 provides a comparison of flow required for interference free and what is obtained with a porous wall along a single ray at a height above the mid semispan of the model's wing corresponding to the ceiling of the transonic tunnel. In Fig. 10, the range of computation extends one body length upstream (+ symbol) and one body length downstream (x symbol) from the respective nose and tail locations of the model. The difference between the linear law (6- and 10-percent Porous boundary condition) and the free-air solution illustrates the idea that a constant resistivity wall can not possibly produce zero wall interference. Moreover, it can be seen that a wall which varies the resistivity in the streamwise direction to better match the free-air curve cannot produce zero interference either. However, 3D calculations performed by Sickles and Steinle[11] showed that by throttling the flow through each slot in a few segments, the wall interference is reduced to an acceptably low level, if the sidewall angle is employed to reduce blockage buoyancy effects. The benefit of a fully adaptive wall is the difference between what can be provided by throttling of the wall in segments versus active blowing and suction. It may be possible to capture some of this effect if PES is employed at subsonic speeds to establish a baseline with reduced boundary-layer thickness and, by throttling the suction, achieve some of the effect of active blowing through the behavior of the boundary-layer growth. Essentially, this is the technology employed by the AEDC 1T Tunnel[16] and later incorporated in T128 tunnel at TSAGI[17]. The use of increased porosity over the 6% wall will provide a match further downstream. For this particular ray, neither 6- nor 10-percent porosity will provide a match over the entire length of the fuselage (solid symbols). Clearly, a still higher maximum porosity capability is preferable to achieve a better match with what is required for free air. However, higher porosity would further compromise the design for optical access. The most important gain is in the ability to close off the slots so flow through the walls is prevented when the basic character of the wall would otherwise aggravate the mismatch between freeair and tunnel. The character of the curve shown in Fig. 10 suggests that control of slot behavior of around 8 - 10 segments over the length of the fuselage should be sufficient. In this case, the length of the fuselage chosen is approximately 18 ft. For 8 segments, the length of each control segment is 30 inches. Initially, a baseline control length of 30 inches for each slot segment was selected. As part of the effort to reduce costs for the MPWT, and in view of the results by Sickles & Steinle,[11] the length of each control segment for the baseline design was increased to 48 inches.

Figure 11 shows similar potential flow results for the low-speed, high-lift condition. Here, a maximum size full-span model is considered. The computation for the low-speed condition shows results similar to the transonic wind tunnel. Control of crossflow would clearly improve the match at the boundary condition. A fully adaptive wall which

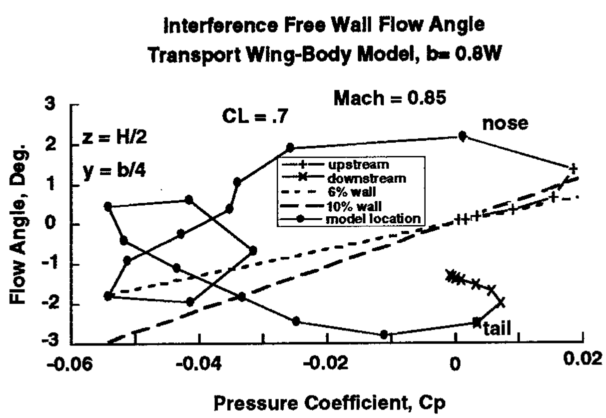


Figure 10. Crossflow variation at upper wall location for wing-body representation at Mach number 0.085 and CL = 0.7.

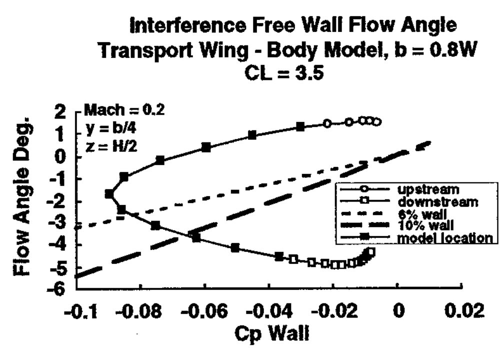


Figure 11. Crossflow variation at upper wall location for wing-body representation at Mach number 0.2 and CL = 3.5.

was well beyond the scope of the NWTC project budget would, of course, be expected to produce the lowest interference.

Flow Quality - Slot Acoustic Tones

The previously mentioned test in the Ames 14-ft tunnel led to the baseline slot-baffle, modified to prevent the generation of strong acoustic resonances. The full details of the test, including configurations tested, is left to the reader to consult the archives of the NWTC project.[10]

A very large, clipped-wing model of a Boeing 747 aircraft used for NASA's SOPHIA project was

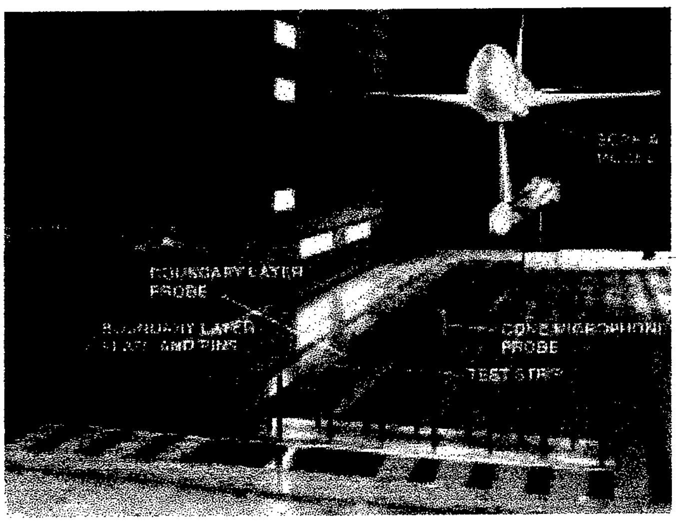


Figure 12. 14-ft wind tunnel test installation photograph.

used to generate a pressure difference across the test specimens installed in the instrumented section of the floor of the 14-ft tunnel (Fig. 12). As seen in the figure (photograph), the floor is solid, except for the strip to the right of model center which was used to install the series of test specimens. At the upstream end of the test section is a plate with a series of pins which was used to create a change in boundary-layer thickness. A thicker boundary layer reduced the overall noise level measured in the slot-baffle channel slightly, and since results with this thicker boundary layer do not change any general conclusions, they are not discussed further. The strip used to test the slot specimens was formed by removing two floor rails and replacing them with different rails which would accommodate the specimens as well as provide an instrumentation bar which had Kulite® transducers installed to obtain static fluctuation pressure measurements from each test specimen. The locations were chosen to permit measuring static pressure at two locations (0.75- and 1.5 in.) below the stream surface in one channel near the center of each test specimen. Also seen in the photograph are two traversing boundary-layer probes (upstream and downstream portion of test section) and a cone microphone probe in the upstream portion of the test section. The traversing probes included a total temperature probe and were normally retracted and used only sparingly to obtain boundary-layer profiles. The details of these boundary-layer measurements are also not discussed herein, but are presented in Ref. 8.

The static pressure distribution imposed on the floor by the SOPHIA model at Mach number 0.85 is shown in Fig. 13. The effect of complete throttling of the flow through the slot with a cut-off plate (100-percent cut-off) can be seen in the change in pressure distribution measured on the slat near the slot specimens. Four locations for Kulite® measurements are marked (K19, K27, K31, and K39). All four of these locations are at the 0.75-in. distance below the stream surface. These locations represent where data was obtained for the baseline slot-baffle configuration (M12-7), and a second specimen

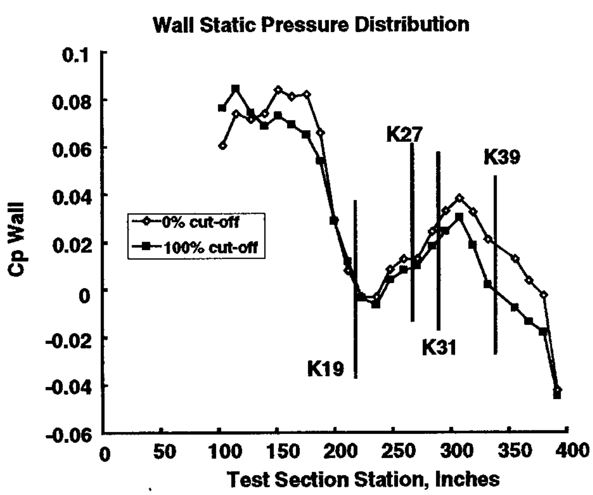


Figure 13. Mach 0.85 floor static pressure distribution.

(M12-7a) which was slightly smaller in the width of the notch by less than 0.04-in. The smaller width notch was the result of hand grinding and not having the time to be precise. As will be seen later, this difference in notch width seems to have had some significance in the test results.

Slot-baffle cavity noise for both the M12-7 and M12-7a specimens in the fully-open configuration is shown in Fig. 14. These data include Mach numbers 0.3, 0.6, and 0.85. Mach numbers are not identified in the figure. However, due to compressibility, increasing magnitude of pressure coefficient is associated with increasing Mach number. The K27 location for the M12-7 configuration shows a high level of noise in Fig. 15a which is not caused by a strong slot noise peak. Instead, it appears to be related to a broadband jet-noise type peak centered around 270 Hz. The Cp wall for this location at Mach 0.85 is approximately 0.012 which implies some outflow. Insufficient information is available to determine the cause of this broadband noise. In Fig. 15b, the spectral results for M12-17a in the K19 location show a substantial noise peak at approximately 1,900 Hz, which is near the resonant tone for the 14-ft wind tunnel slots at this Mach number. On the other hand, the M12-7 at the K19 location (Fig. 15c) does not exhibit this peak. Apparently, the slightly larger notch width in the M12-7 configuration was sufficient to suppress a resonant peak. On the other hand, the spectral content for the M12-7 is considerably flatter than for the M12-7a at the K-19 location. Results for the M12-7a configuration at the K31 location (Cp wall = 0.028) are shown in Fig. 15d. No apparent slot tone is evident at this condition. Figure 15-e shows the results for the M12-7 specimen at the K19 location with the baffle 100-percent cut off. No significant noise peak is evident. However, there is a

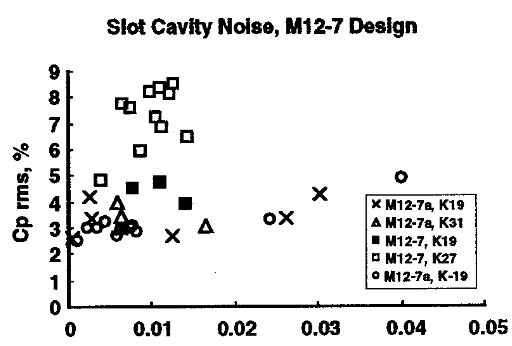
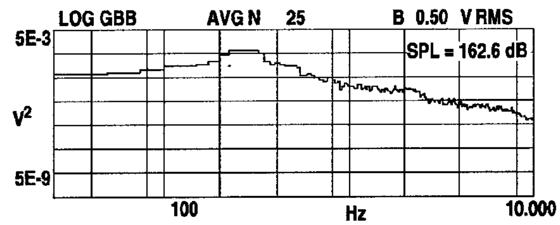
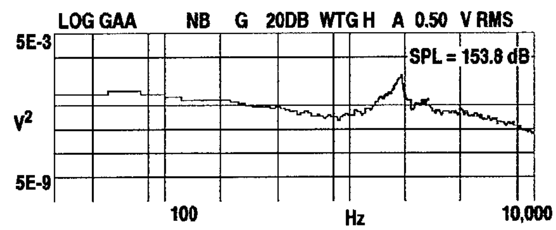


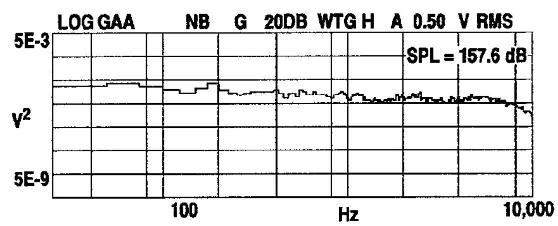
Figure 14. Slot-baffle channel noise for baseline configuration.



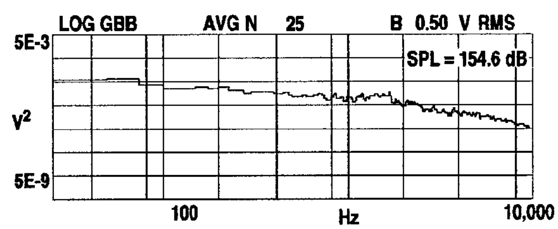
a. M12-7, K27



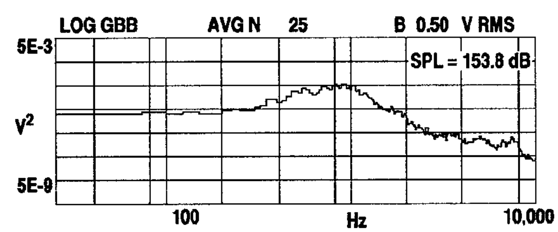
b. M12-7a, K19



c. M12-7, K19



d. M12-7a, K31



e. M12-7, K19

Figure 15. Mach 0.85 noise spectra for baseline slot-baffle configuration.

strong broadband noise centered around 900 Hz. The rms noise level resulting from this condition is the same as for the M12-7a, fully open, specimen at the same K19 location.

Other data for the M12-7 and M12-7a specimens are not shown since they will not add anything to the general observations made above. The test was successful in that a starting point for further work which did not exhibit slot tones over the range of conditions investigated was identified.

Concluding Remarks

Although with the NWTC project was not continued through the detailed design phase to completion, much was accomplished in many areas, including test section design concepts. An excellent starting point for further development of a transonic wind tunnel test section concept applicable either to a retrofit of existing test sections or the development of an entirely new test section resulted from the NWTC project. Obviously, the NWTC requirements for flow quality, including wall interference, which were judged by NASA, DoD, and Industry representatives as bona-fide cannot be met with the technology currently employed in our wind tunnels. A focused effort to bring to fruition test section technology concepts or their equivalent which ensued from the NWTC project is warranted on the basis of the established need.

A baseline design which afforded a substantial amount of optical viewing area and a variable characteristic porous-slotted wall concept was identified that was expected to have very good flow quality features, and improved wall interference without producing a strong acoustic resonant peak. However, problems remain to be solved. In particular, slot-related broadband noise problems will require continued experimental development. Moreover, there is always the potential for some resonance to be masked by the broadband noise evident and the possibility that a wider range of test conditions may produce a resonant peak.

The problem of having a ventilated test section wall that does not generate a high noise level at some critical test condition is far from solved. However, the results from the initial NWTC development effort show promise. It is inescapable that having slots results in jet flow interactions which produce noise. Limitations on the width of the slot for optical viewing and the need to accommodate large models imply a fairly large range of mass flow through the slots. This leads to a substantial challenge in holding the jet noise generated to a minimum. Sources for the broadband noise can be external from the model, jet noise interaction due to the flow out of the slot into the plenum chamber, and interaction with the flow entering the slot-baffle channels and interacting with the notched baffle segments. Clearly, further work is needed to improve the configuration to reduce the broadband noise generated by the slot flow while simultaneously not having a slot noise resonance problem.

Structural analysis may show that the M12-7 configuration was too robust and that by reducing plate thickness a more open passage which would reduce jet noise associated with slot flow is possible. A cleaner aerodynamic configuration may be better. Other concepts than were tested may produce better results. The use of other sound-absorbent materials or coatings such as urethane (suggested by Ron Krueger) may be acceptable and preferable.

Improvements in the test procedure, scope of data, and analysis are warranted. Variables to test include:

- better set of acoustic instrumentation and data reduction procedures to permit identification of noise sources;
- a full range of boundary-layer thickness for a given tunnel, longer test specimens to provide a complete development of local slot flow;
- controlled suction and blowing through a slot segment for both noise and crossflow resistance;
- extension of the scope of the test to more than one slot so that 3D boundary-layer changes can be investigated with application to wall boundary conditions;
- static pressure measurements on the slats and the use of pressure-sensitive paint to

visualize the pressure distribution on slats; and

- use of LV measurements or traversing flow-angle probes to determine local flow conditions at the edge of the boundary layer so that improved wall boundary conditions with an analytic extension can be developed and validated.

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The contributions of the key personnel supporting the 14-ft test program deserve special recognition. Personnel from Calspan-Ames provided the detailed design and oversight of fabrication of the test specimens (Ron Krueger), planning and test program coordination and leadership (George Rupp), instrumentation engineering (Mike Simundich) and technician support (Howard Clark), and tunnel operations and model change support (Ty Yuen, Oscar Rodriguez, and Ralph Lopez). Dynamic data acquisition, processing, and consultation was provided by Rose Engineering, Inc. (Bill Rose). The test was accomplished as a production test rather than the developmental R&D test that it was and it required the full support and cooperation of the entire team, including flexibility in work schedule to achieve the desired result. It could not have been successful without their extraordinary support.

References

1. Davis, John W., Stamper, and Bill; Wiggum, Paul. "The National Wind Tunnel - Current Status." AIAA Paper No. 96-0226, AIAA 34th Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 15-18, 1996.

2. Ring, Leon, et. al. "NWTC Final Report." NASA CR-198491, June 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vol. No. 1, Electronic Document: nwtcfnl.htm, pp. 1-3.

3. *Ibid.*, 2, p. 2.

4. *Ibid.*, 2, pp. 27-28.

5. Crites, R.C. and Steinle, F.W., Jr. "Wall Interference Reduction Methods for Subsonic Tunnels." AIAA Paper No. 95-0107, AIAA 33st Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.

6. Allen, H.J. "Transonic Wind Tunnel Development of the National Advisory Committee for Aeronautics." AGARD AG17/P7, 6th Meeting of the Wind Tunnel and Model Testing Panel, Pari,s France, Nov. 2-6, 1954, p. 217.

7. Dougherty, N.S., Jr. "An Experimental Investigation of the Acoustic Characteristics of a Variety of Slot-Baffle Configurations for Transonic Wind Tunnel Walls." AEDC TR-79-16 (AD-A070-261), June, 1979.

8. Jacocks, J. L., Sinclair, D. W., and Parker, R.L., Jr. "Evaluation of the Acoustic and Aerodynamic Characteristics of Several Slot-Baffle Configurations for Transonic Wind Tunnel Walls." AEDC TR 79-59 (AD-A093-957), January 1981.

9. Bussoletti, J.E., Krynytzky, A.J., and Lundry, J.L. "CES 4-01 Slot Aerodynamics Study." NASA CR-198491, June, 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vol. No. 3, Electronic Document: d330.htm.

10. Steinle, F.W., Jr. and Rupp, G. "Slot-Baffle Acoustics Test and Data Analysis Report." NASA CR-198491, June 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vols. No. 6 & 1, Electronic Document: d650.htm.

11. Sickles, W.L. and Steinle, F.W., Jr. "NWTC Slotted Wall Design Effort: Computational Task." NASA CR-198491, June 1996, Archives of the National Wind Tunnel Complex, CD ROM Vol. No. 1, Electronic Document: d648.htm.

12. Perino, J. "Change Request - CR#7, Single Tunnel SDR Baseline." "NASA CR-198491, June 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vol. No. 1, Electronic Document: cr_7.doc.

13. "Test PDT; Carts, Balances, Test, & Equipment Systems PDT." NASA CR-198491, June, 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vol. No. 3, Electronic Document: testcalc.htm, file: /scandocs/dt54p062 - p064.

14. "NWTC: Single Tunnel System Design Review (SDR)." NASA CR-198491, June 1996, Archives of the National Wind Tunnel Complex, CD ROM Vol. No. 5, Electronic Document: sdr1t.htm.

15. Steinle, F.W., Jr. "NWTC Slotted Wall Design." NASA CR-198491, June, 1996, Archives of the National Wind Tunnel Complex, CD-ROM Vol. No. 1, Electronic Document: cr95_025.doc.

16. Parker, R.L., Jr. and Erickson, J.C., Jr., Development of a Three-Dimensional Adaptive Wall Test Section With Perforated Walls, 50th AGARD Fluid Dynamics Panel Specialist Meeting on Wall Interference in Wind Tunnels, London, England, May 19-20. AGARD - CP - 335 (N1983 - 20957#), Paper no. 17.

17. Cjakowski, Dr. Eva."Russian Aeronautical Test Facilities." ANSER Center for International Aerospace Cooperation, 1215 Jefferson Davis Highway, Suite 800, Arlington, VA 22202-3251, 1994, pp. 2-50-51.

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The development of the concept features of the wall configuration of the National Wind Tunnel Complex project is described in the context of the project history. Flow quality requirements concerning stream angle homogeneity at the outer edge of the test volume, requirements for maximum wall interference, optical access, and test volume acoustic considerations in addition to Mach number range and tunnel operational mode were factors in the design. The development process included 2D calculations for stream angle homogeneity to establish slot width and spacing, 3D calculations for verification of slot geometry and crossflow control, and experimental development of slotbaffle insert geometry that would be rugged, allow control of crossflow, and not produce strong resonant tones. results of 2D calculations, 3D calculations to illustrate need for control of crossflow, and experimental evaluation of baseline slotbaffle acoustic properties are presented.

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